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Abstract. We have used the EBIT Calorimeter Spectrometer (ECS), a microcalorimeter instrument built by the calorimeter group at the NASA/Goddard Space Flight Center, to make a variety of measurements since its installation at Lawrence Livermore National Laboratory's EBIT facility. These include measurements of charge exchange between neutral gas and K- and L- shell ions, measurements of the X-ray transmission efficiency of optical blocking filters, high resolution measurements of transition energies for high-Z, highly charged ions, and measurements of M and L-shell emission from highly charged tungsten following on earlier measurements of L-shell gold. Our results will see application in the interpretation of the spectra from the Jovian atmosphere and of the diffuse soft X-ray background, in tests of QED, and in diagnosing inertial and magnetic confinement fusion plasmas. These measurements augment previous laboratory astrophysics, atomic physics, and calibration measurements made using earlier versions of NASA's microcalorimeter spectrometer.

Keywords: X-ray, X-ray spectroscopy, calorimeter, astrophysics,QED
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X-ray calorimeters built at the NASA/Goddard Space Flight Center have been used at Lawrence Livermore National Laboratory's (LLNL) Electron Beam Ion Trap (EBIT) facility beginning in 2000 [1, 2, 3]. Since then, three different versions of the NASA/GSFC calorimeter instrument have operated at LLNL, the most recent being the EBIT Calorimeter Spectrometer (ECS) [4, 5]. The ECS consists of 32 silicon thermister pixels, 18 affixed with 8 μm thick HgTe absorbers for measurements in the 0.05 to 12 keV band, and 14 affixed with 100 μm thick HgTe absorbers for measurements covering the 0.3 to 100 keV band. The 8 μm pixels have an energy resolution of $\sim$ 4.5 eV (FWHM) at 6 keV with 95% quantum efficiency, and the 100 μm pixels have a resolution of 33 eV (FWHM) at 60 keV with a QE of 32% (see [5] for more details). Because of its high spectral resolution, broad bandwidth, high quantum efficiency, and the fact that the energy resolution does not depend on the size of the X-ray source, the ECS and its predecessors have become the "workhorse" spectrometers at the LLNL EBIT facility. They have been used to measure absolute excitation cross sections [6, 7], line energies [8], spectral signatures of charge exchange recombination [9, 10], in lifetime measurements [11], in a variety of laboratory astrophysics experiments, and to measure the transmittance of optical blocking filters [12]. Here we give a brief description of a few of the more recent measurements using the microcalorimeter instruments at the LLNL EBIT facility.

EBIT was invented at LLNL and was built and developed as a tool to make high-accuracy measurements of atomic structure [13, 14, 15]. The main components of EBIT are an electron beam, a trap region, and a beam collector. The electron beam is used to radially trap, ionize, and excite ions. Ions are trapped axially by three drift tubes. Once the beam passes through the trap region, it is collected by a collector electrode. Details of the operation of EBIT can be found elsewhere [16].

Charge exchange (CX) recombination is the radiationless transfer of one or more electron from a neutral atom or molecule to an ion. X-rays are produced from CX when the transferred electron radiatively decays. CX takes place in celestial and laboratory sources. Owing to the fact that relatively little laboratory data exist, and in many cases CX spectral signatures are not well known, the diagnostic capability of CX emission has not been fully realized. To address this problem, EBIT and the ECS have been used to measure the X-ray spectral signatures of CX recombination. At EBIT, X-ray emission from charge exchange is produced using the magnetic trapping mode [17]. In this mode, the electron beam is turned off and the ions are trapped radially by the magnetic field of the superconducting magnet usually used to compress the electron beam. Neu-

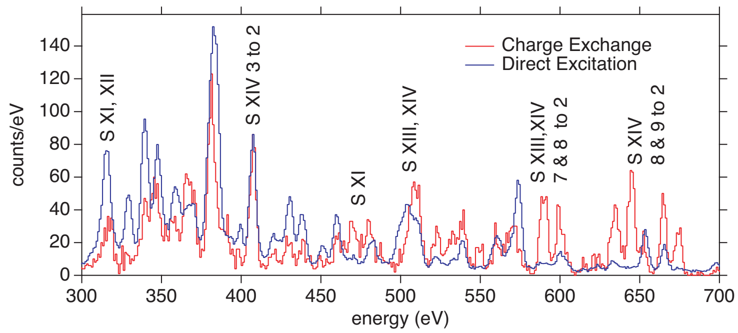

FIGURE 1. Comparison of direct excitation to charge exchange produced spectra of L-shell sulfur ions. Both spectra were measured with the EBIT Calorimeter Spectrometer. Some of the stronger lines are labelled. See [10] for a complete description of the measurement. (Color online)

tral material, introduced in the trap region using a ballistic gas injector, then interacts with the ions, CX occurs and X-rays are produced. Because the beam is not present in the magnetic mode, the ions are no longer localized to the 60 μm electron beam diameter and therefore represent an extended source of X-ray emission. The ability of the NASA/GSFC microcalorimeter to measure high-resolution spectra from extended sources without a degradation in energy resolution, and to measure time-resolved spectra, make it perfectly suited to measure the spectral signature of CX reactions produced in EBIT. Several CX measurements have been completed using the NASA/GSFC microcalorimeter instruments [9, 18, 19]. Recently, we have used the ECS to measure the CX signature of L-shell ions of sulfur. Because these transitions fall in the energy band below 500 eV, their measurement is largely facilitated by the relatively thin thermal blocking filters employed by the ECS. Figure 1 shows a comparison of the direct excitation spectrum and the spectrum produced by CX. These spectra are being used to interpret the X-ray emission from the aurora of Jupiter and also of the soft X-ray background [10, 20].

Tungsten is being employed as an internal coating for magnetic fusion devices and will be the material used for the divertor in the International Thermonuclear Experimental Reactor (ITER). As a result, it will be present in many fusion plasmas. At the temperature of the higher energy devices, several middle charge state W ions will be present. Accurate knowledge of the emission line wavelengths and excitation cross sections are crucial for tapping the W X-ray spectra of its full diagnostic potential. To provide benchmarks for atomic codes used to model these spectra, the ECS is being used to measure X-ray emission from both M-shell and L-shell inter- and intra-shell transitions. Figure 2 shows a broadband spectrum of X-ray emission from M-shell transitions in Ni-like W^{46+} and Co-like W^{47+} [21].

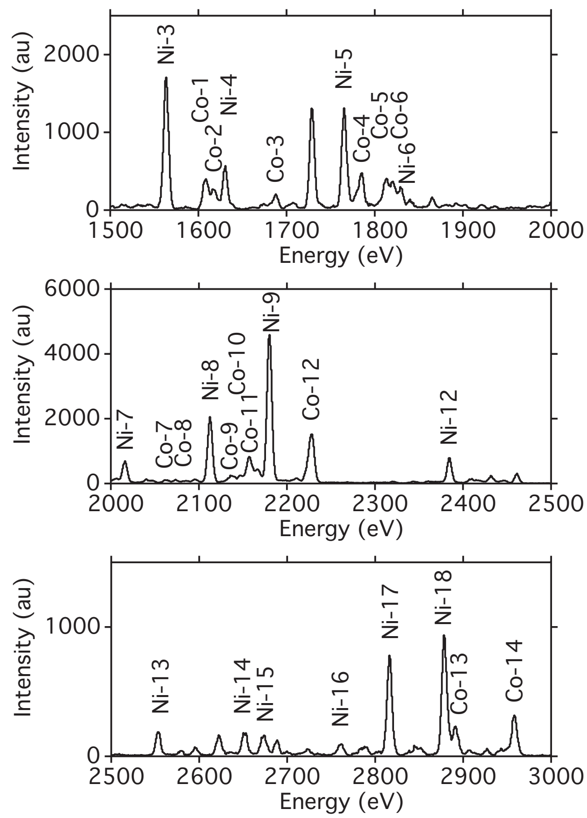

FIGURE 2. Broadband spectrum of M-shell transitions in Co- and Ni-like W. The spectrum is divided into three pieces for easier viewing. The lines are labeled according to thier charge state, i.e. Ni-3 is from Nickel-like W^{46+}. This spectrum was measured with the XRS/EBIT spectrometer, the second generation NASA/GSFC calorimeter in operation at LLNL [21].

The NASA/GSFC calorimeters have also been used to benchmark atomic codes used to interpret spectra from high-density, laser-produced plasmas and inertial con-

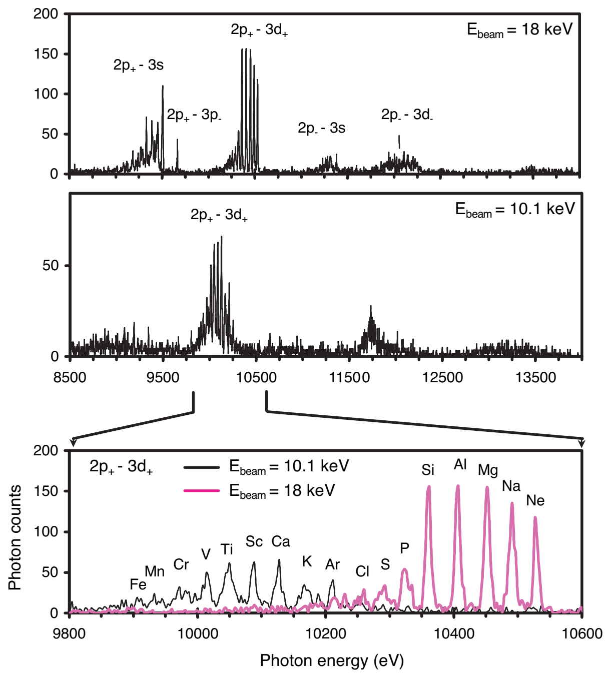

FIGURE 3. High resolution spectra of L-shell transitions in highly charged gold ions. The top figure was measured at an electron beam energy of 18 keV and shows strong emission from Si-like Au^{65+} to Ne-like Au^{69+}. The middle figure was measured at an electron beam energy of 10.1 keV and contains emission from several lower charge states between Fe-like Au^{53+} and Ar-like Au^{61+}. The bottom figure shows an expanded view of the 9800 to 10600 eV band [8].

finement fusion plasmas. Gold hohlraums are often employed as targets for inertial confinement fusion studies. In these studies, electron temperatures in the laser plasma interaction region have been predicted as high as 30 keV and Thomson scattering experiments have measured temperatures as high as 50 keV, although with high uncertainty owing to the fact that the average ionization state of gold ions is not well known. Gold L-shell radiation is produced in plasmas with electron temperatures in the 30–50 keV band. If resolved, this radiation creates a “picket-fence” spectral structure where each line or “post” is produced by a different charge state. In the past, uncertainties in the calculations have made it very challenging to unambiguously determine which charge state produced which line feature. To address this problem, we have used the calorimeter and the LLNL EBIT to measure the line energies of the L-shell transitions in highly charged gold ions. For these experiments, gold was injected using the laser ablation injection system [22], and the energy scale was calibrated using K-shell emission from Ar, Ni, and Ge. Figure 3 shows the spectra measured at 18 keV, one at 10.1 keV, and also an expanded view of the region with the strongest line emission. In the bottom figure, the “picket-fence” structure is easily seen and the emission from several different charge states is easily resolved. A detailed description of this experiment and the theoretical study can be found in [8].

In addition to the L- and M-shell transitions in high-Z ions, measurements of the transition energies of K-shell emission from high-Z ions have also been measured using the ECS. For example, the high-energy pixels have been used to measure the emission from helium-like Xe^{52+} and hydrogenic Xe^{53+} (see figure 6 of Porter et al., in these proceedings). The high resolution and QE of the high energy pixels made it possible to measure the transition energies to high accuracy, and to resolve some lines for the first time. The results of these measurements have been used to distinguish among different calculations of QED contributions to the transition energies [23].

The utility of the ECS-EBIT combination goes beyond measurements of atomic physics parameters and laboratory astrophysics studies. It has also been used to measure the absolute X-ray transmittance of thin filters [8]. Many spectral diagnostics employ thin filters of either pure metals or metalized plastic to filter out unwanted radiation or to provide energy calibration fiducials created by absorption edges. Because the X-ray transmittance of these filters is energy dependent, proper analysis of the detected radiation requires an accurate knowledge of the transmittance as a function of energy. Although manufacturers often do an excellent job of determining thickness, the quoted uncertainty in the thickness often translates to an error in transmittance larger than required to achieve experimental goals, and most manufacturers do not provide X-ray transmittance data. We have developed a system to measure the absolute transmittance of thin filters. In our method we translate the filter in and out of the line of sight of the X-ray radiation from EBIT to the ECS. By dividing the strength of the X-ray line radiation measured with the filter in by the spectrum with the filter out, the absolute filter transmission is determined. As an example, Figure 4 shows the results of a measurement of the transmittance of an aluminized lexan filter manufactured by the Luxel corporation. To span the energy range from below the carbon edge to above the aluminum edge, X-ray radiation produced by K-shell transitions in B, C, N, O, and Ne were used, as well as L-shell transitions in neon-like Kr. The advantage of using the ECS as a detector is that its high energy resolution and broad bandwidth make it possible to easily determine the X-ray transmittance at several discrete X-ray energies simultaneously; hence, the transmittance as a function of energy can be rapidly determined. The total time required to determine the complete X-ray transmittance across the 200 to 2000 eV energy band for the Luxel filter was 6 hours.

Here we have shown the large range of measurements made possible by the ECS and the previous NASA/GSFC calorimeter instruments operated at the LLNL EBIT fa-

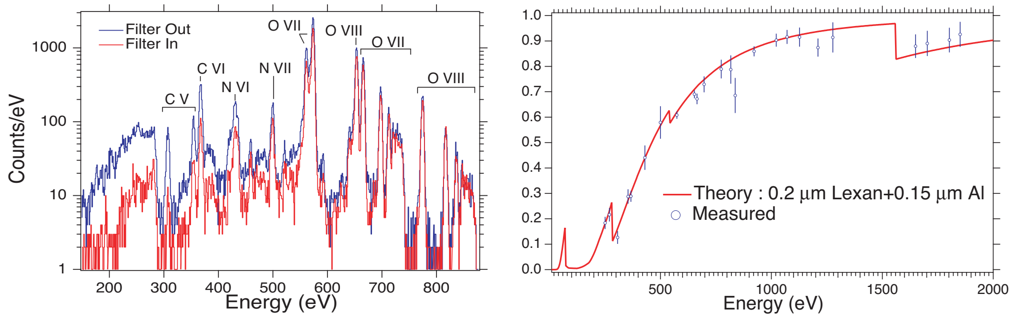

FIGURE 4. (Left) Comparison of the spectra measured by the ECS to determine the absolute X-ray transmittance of the aluminized lexan filter across the 150 to 900 eV energy band. (Right) Measured compared to theoretical transmittance. Theory based on data from the Center for X-ray optics and the nominal thickness of the filter given by the manufacturer [12].

cility. The ECS will continue to be employed as one of the primary spectrometers used daily at LLNL.

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